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Dust effect on flat surfaces – A review paper

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ABSTRACT

Dust accumulation is one of the natural phenomena that adversely affects the performance of solar systems. Since 1942, many efforts have been made to address the severity of deposited particles like dust, water stains, carbon from smoke, pollen in agricultural regions, etc. on the efficiency reduction of solar devices, which results in additional costs either from oversizing the system or from cleaning it. Although various innovative methods have been employed to clean the surface of grimy PVs, a holistic approach needs to show the cleaning mechanism under different climate conditions. This review highlights the findings from several references in three time periods and focusing on their similarities. For scaling up the appropriate mitigation method, four different global zones are explored based on suspended particles in the air. Consequently, the pattern of dust distribution in different parts of the world is assessed and it was found that the Middle East and North Africa have the worst dust accumulation zones in the world. Finally, a set of recommendations and guidelines with regard to the different climatic zones and their characteristics are presented especially for the installers of PV or other solar devices to implement a suitable cleaning system.

Contents

1. Introduction

The use of solar energy increased by 50% from 2003 to 2008 and is estimated it will continue at a growth rate of at least 25% annually [1]. Large scale solar power plants already have been installed in many parts of the world including the United States, Spain, Germany, the Middle East, Australia and India. These installations are usually located at high solar radiation intensity zones such as in desert areas where it has a dry and windy weather. The wind normally sweeps the dust from the solar devices but stays suspended into the air, which can result in an adverse effect resulting in less solar radiation reaching the solar devices. Also, suspended dust, whether fine or large, in the atmosphere eventually will settle on the solar panels and cover their surfaces and therefore reduce their efficiencies. Another disadvantage of having suspended dust particles is they reflect solar radiation and hence reduce the solar gain reaching the devices to generate power or electricity such as photovoltaic, flat plate solar collectors and concentrating solar power devices (CSP). In arid, semi-arid zones, and desert regions dust storms and suspended micro-particles in the air often occur and need to be

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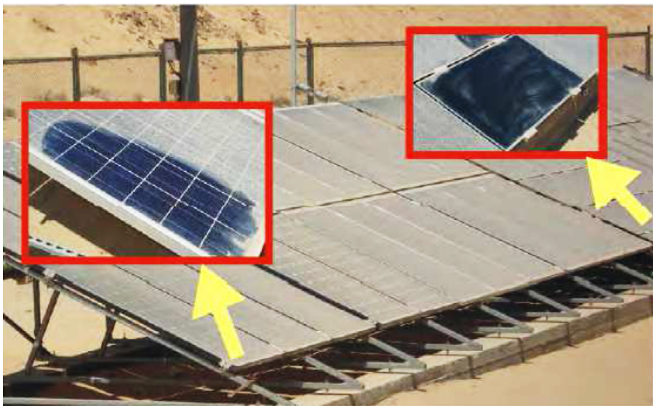

Fig. 1. Dust layer accumulation on PV modules in Egypt [3].

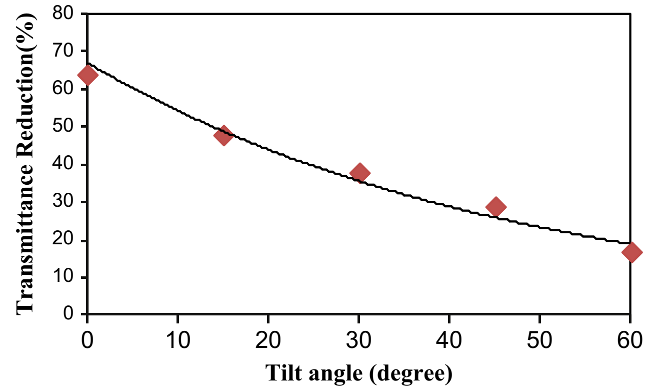

Fig. 2. Variation of transmissivity decrease percentage versus title angle for dust accumulation on a flat glass at Riyadh, Saudi Arabia in 1977.

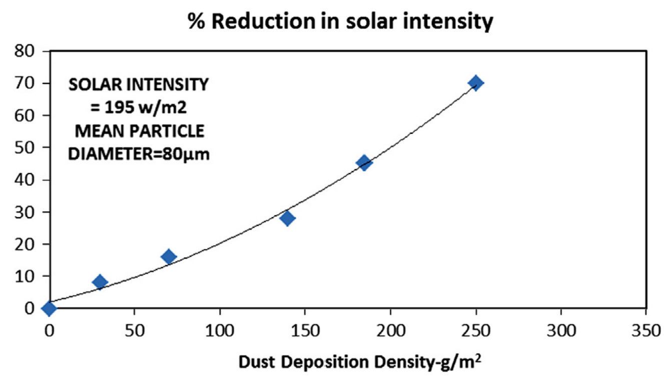

Fig. 3. Solar intensity reduction versus amount of dust deposition density [7].

managed in planning the site or through the use of cleaning mechanisms. For example, in just one hour, a desert sand storm can plaster even the toughest solar panels with a thick layer of residue, reducing their efficiency by upwards of 70–80%. If the panels are not cleaned regularly or almost daily, they become practically useless. Moreover, these areas suffer from water shortage, which leads to a relatively expensive cleaning mechanism. Fig. 1 shows the soiling accumulation after a period of one year for the systems installed in Egypt. The energy production results showed a dusty module produced 25 and 35% lower energy compared to a clean module after a period of three months and one year, respectively[2,3].

From 1942 to the present a number of research has been conducted on the adverse effect of dust on solar PVs and solar thermal devices. Moreover, several reviews have been published recently, which cover a wide range of studies dealing with dust impact on solar systems, mitigation approach and cleaning mechanisms. In this review, examination of the state of the art by presenting the results of some experiments and studies in different periods of time and different places will be analysed. Also, it emphasises, the importance of different climate conditions, as a significant factor for accumulating of dust and particles on solar systems and a framework needs to be provided for the cleaning mechanism of PV panels or exposed solar devices all over the world.

2. The state of the art

Early research on dust and deposition effect on PV panels and solar thermal devices dates back to more than seventy years ago. Initial studies were focused mainly on the thermal cells and dust effect on the mirror reflectance [4]. For instance, Sayigh [5] conducted a detailed investigation on the effect of dust on solar flat-plate collectors. The experiment comprised seven flat plate collectors, with six arranged in pairs and subjected to various inclinations of 0°, 30°, and 60°, with the seventh collector inclined vertically at 90°. In each pair one collector was cleaned regularly while the other was kept undisturbed. The amount of absorbed solar energy of the unclean plates was computed and compared to that of the cleaned ones. It indicated a dust collection of about 2.5 g/m^2/day between April and June 1978. Sayigh et al. [6] also investigated the effect of dust accumulation on tilted glass plates located in Kuwait and found a reduction in plate-transmittance by an amount ranging from 64% to 17% for tilt angles ranging from 0° to 60°, respectively, after 38 days of exposure in 1985. In addition, a reduction of 30% in useful energy gain was observed by the horizontal collector after 3 days of dust accumulation. The influence of tilt angle on dust-covered glass reduction in solar transmittance is illustrated in Fig. 2.

Fig. 3 shows the percentage of solar intensity reduction versus the amount of dust deposition (g/m^2) under a constant solar intensity of 196 W/m^{2}and dust particles size 80 μm, [7].

The work of Sayigh [5,6] in the 1970s and the 1980s highlighted a major problem regarding dust in the Gulf Region. Figs. 4 and 5 show collectors and glass samples under environmental conditions in Riyadh and Kuwait during different tests in the period 1977–1985.

Fig. 6 shows two collectors subjected to two weeks' weather conditions during the summer period. A – was inclined at 45° in Riyadh, Saudi Arabia, the dust accumulation is clearly more at the lower parts of the collector, B – a different collector which was in Kuwait close to the sea, the dust was mixed with the humidity and cemented itself onto the glass cover.

In 1978, research has updated information that deals with solar photovoltaic panels. A study by Salim et al. [8] discusses the long-term dust accumulation on a solar-village PV system near Riyadh, Saudi Arabia, which indicated a 32% reduction, after 8 months, in performance of the solar array due to dust accumulation. This was in comparison with an identical PV system tilted at 24.6° that was cleaned daily. On similar lines, a study carried out by Wakim [9] in Kuwait city showed a reduction in PV power by 17% due to sand accumulation on panels after 6 days. Further, the study also highlighted that the influence of dust on PV performance was higher in spring and summer (20% in 6 months) than in autumn and winter.

In this context, after 1990 many experiments have been conducted to test the effect of dust on the solar panels in terms of the collected power, the effect of particle size, the effect of wind on the accumulated dust, and the effect of different types of dust,

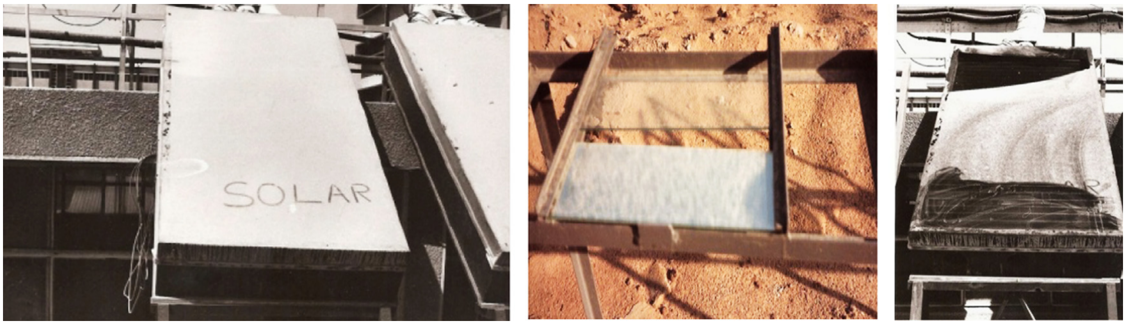

Fig. 4. Dust effect on flat covers, glass and plastics in Riyadh and Kuwait.

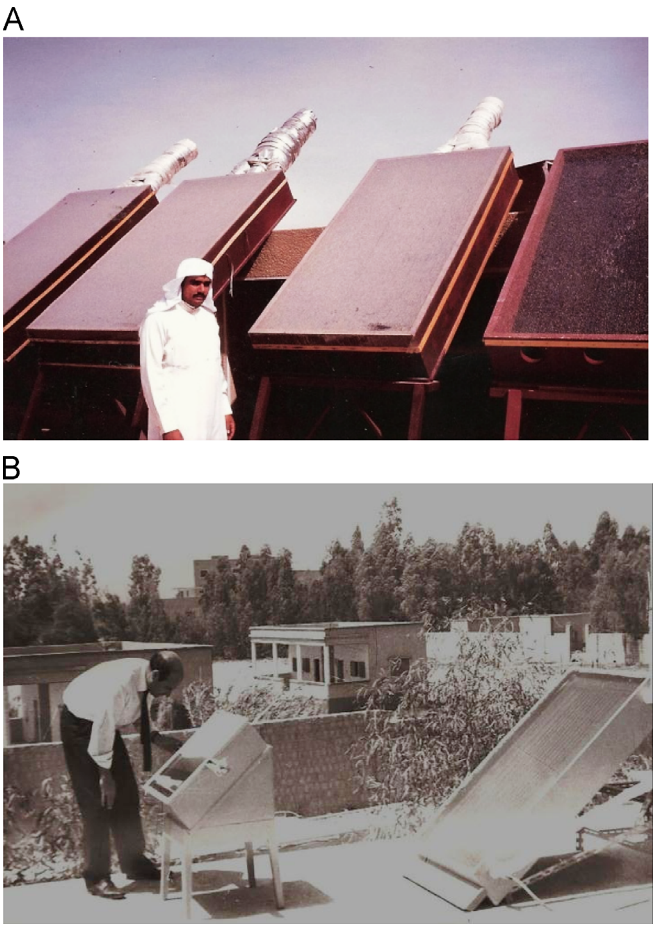

Fig. 5. Dust effect on tilted collectors after 10 days without cleaning in Saudi Arabia.

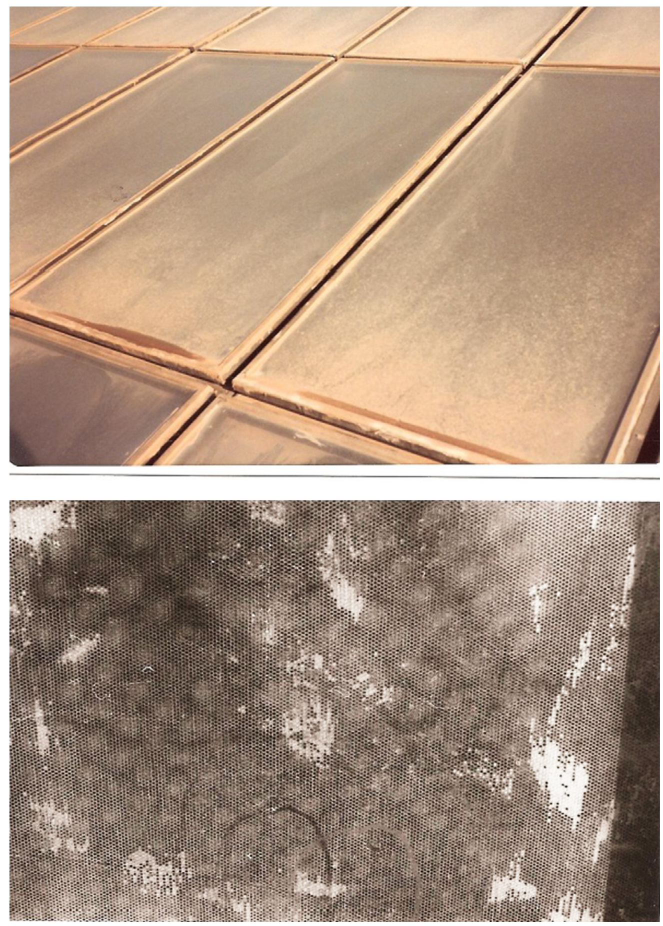

Fig. 6. Two collectors, one in Riyadh and another in Kuwait.

including limestone, cement and carbon [10]. Soil and sand depositions are among the primary sources of natural degradation, among other airborne particulates, chemical weathering processes, as well as industrial carbon and other types of dirt. In 2010 and later, there have been a number of studies concerning the degradation of the performance of solar photovoltaic and thermal panels arising from environmental factors [11–13]. Many collectors show lower performance efficiency after a short period of time, both in electrical and in thermal performance capabilities. Most panels are designed with the intention of correct operation for over two decades; however, their performance time is reduced by environmental conditions of the area, especially with settling dust. At that time, Mani and Phili [13] carried out a review paper on the dust effects on PV. They categorised the existing studies and experiments in 3 phases of time. Also, they recommended a useful cleaning cycle to mitigate the impact of dust on PV performance with regard to different climatic zones and characteristics. In recent years in Malaysia Sulaiman et al. [14] used two artificial dusts of different layers on a mono-crystalline PV panel of 50 W, with indoor light simulator. The panel first was tested under clean condition, then was covered with 41 μm layer of mud and tested under the same conditions. This was repeated with a different cover of 103 μm of talcum. They found the reduction in the peak power was up to 18%. In Greece Kaldellis and Capsali [15] simulated the dust effect on the energy performance of photovoltaic generators. The authors found that reduction of PV energy performance depends strongly on particles composition type and sizes. They chose three samples, ash $< 10\ \mu m$, limestone $< 60\ \mu m$, and red soil $< 150\ \mu m$. Additionally, the results showed the particles' deposition is directly proportional to the inclination of the PV panels. Using the terms: polluted capacity factor CFj,

cleaned capacity factor CFo, coefficient Aj (where j represents the type of pollutant), and the total mass of dust deposition ΔM, Kaldellis derived an exponential function of the general form.

$$\mathrm{CFj} = \mathrm{CFo}.e^{-\mathrm{Aj}.\Delta M\mathrm{j}}$$

where Aj depends significantly on the particle sizes mainly: 0.06, 0.1 and 0.24 for the above three kinds of dust, ash, limestone and red soil.

The effect of dust on a set of mono-crystalline panels in Israel for a period of one month was investigated by Boykiw [16]. She measured the effect of dust on their electrical output in one week and also in one month and compared them with the clean panels. Based on the data gathered, dust can cause 5–6% decrease in panel efficiency after one week. But because of rain and construction activities in the area, it was difficult to reach a conclusive result regarding longer time periods. Sanusi [17] tested Amorphous Silicon PV in Nigeria under severe weather conditions in the dusty season, during December, January and February in 2007 and 2008 and found that for 70 days without cleaning there was a 20% reduction in solar absorption. The panels were in horizontal positions. He also introduced two solar radiation scattering formulae due to dust particles or aerosols from Iqbal [18]. They were the Rayleigh Theory for spherical particles having diameters smaller than the light wavelength (λ) and Mie's theory for any particle size. That is:

Case 1:

$$\boldsymbol{\pi} D/\boldsymbol{\lambda} < \mathbf{0.6}/\boldsymbol{n}$$

where D is the particle diameter, n is the refraction index, then scattering is governed by Rayleigh's theory, and
Case 2:

$$\boldsymbol{\pi} D/\boldsymbol{\lambda} > \mathbf{0.6}$$

then scattering is a reflection
Case 3:

$$\mathbf{0.6}/\boldsymbol{n} < \boldsymbol{\pi D}/\boldsymbol{\lambda} < \mathbf{0.6}$$

scattering is governed by Mie's theory

Mie's dust scattering coefficient (K_d) is: $K_d = 0.08128\lambda^{-0.75}$
This is valid for a wide range of number of particles per cubic centimetre (m_a), (from 1 to 800).
Therefore the spectral transmittance (T_d) can be expressed as

$$T_d = \exp[-0.08128\lambda^{-0.75}(D/800)m_a] = \exp[-K_d(D/800)m_a]$$

On the contrary, Rajput et al. [19] used a crystalline PV panel of 0.404 m^2 in Bhopal, latitude 23° 25′ N, at the same tilt angle as the latitude, and found that the dust effect reduces the power output by 92.11% and the efficiency by almost the same value. They defined the reduction of power output as

Percentage power reduction = [Power (without dust)–Power (with dust)]/Power (without dust)

Ali Omar Mohamed et al. [20] tested several polycrystalline panels in Libya during February–May 2011 and discovered that dust effect can contribute to 50% reduction in the panel power output. Weekly wash reduced this to 2–2.5%.

Another observation of dust effect was carried out in Oman by Charabi et al. [21,22], which showed that any cleaned PV panels can have a power reduction as much as 64% if they were not cleaned regularly. And Qasam et al. [23] showed that when a Si panel was subjected to solar radiation and covered by 8.5 mg/cm^2, it exhibited transmittance reduction by 33%. Similar experiments were carried out on crystalline silicon and CIGS panels, and the reductions were 28.6% and 28.5%, respectively. One of the most comprehensive studies of dust is that of Christo [24], which was carried out in southern Australia on a concentrating dish having an area of 425 m^2. He assumed dry sand having a density of 220 kg/m^3, with spherical shape with a Rosin-Rammler size distribution in the range (1–100) μg and a flow rate of 7.8 μg per second; this simulated the actual dust measurements of dust deposition rate collected at a specific location in regional South Australia. Particle velocity was assumed to have the same speed as the prevailing wind speed and dust particles that impact the solid boundary of the dish are deposited on its surface. This represented the worst dust effect scenario. The wind speed was assumed constant at 15.2 m/s and the particles travelled over a distance of 60 m downstream towards the dish. It was discovered that the dust condition increased linearly with the pitch angle of (30°—120°), while in the afternoon the dish orientation was (120°–150°), which is the critical condition for dust accumulation. Fig. 7 shows the dish axes and Fig. 8 shows the dust accumulation versus the dish pitch angle [24]. The author also tried to investigate the case when a layer of dust, 2 mm thick, covers the dish surface.

Another environmental phenomenon which has adverse effects on the efficiency of PV panels is bird droppings. These noticeable deposits can be left on the panels for a while and tend to completely block the light from areas of the photovoltaic panel and can considerably reduce its effectiveness. Dorobantu et al. [25] investigated the effect of impurities deposited on the surface of polycrystalline panels located at Politehnica University of Bucharest, Romania, using a thermo-vision camera. In the image captured with

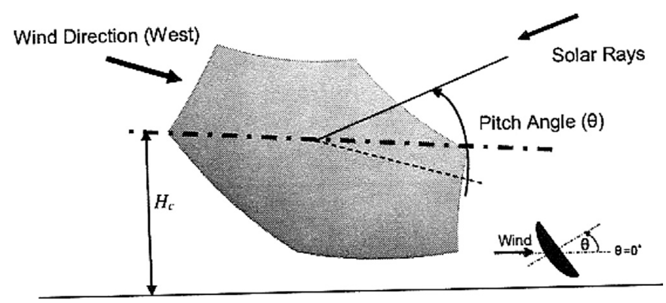

Fig. 7. Dish orientation showing its pitch angle [24].

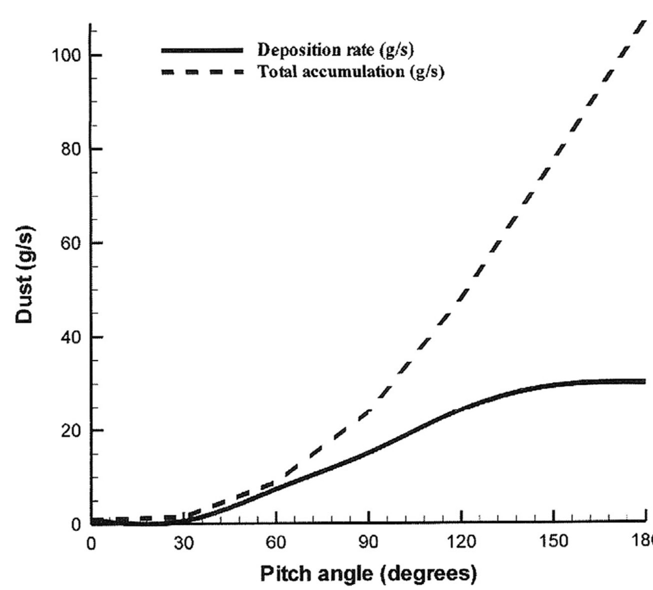

Fig. 8. Dust accumulation in (g/s) versus Dish Pitch Angle [24].

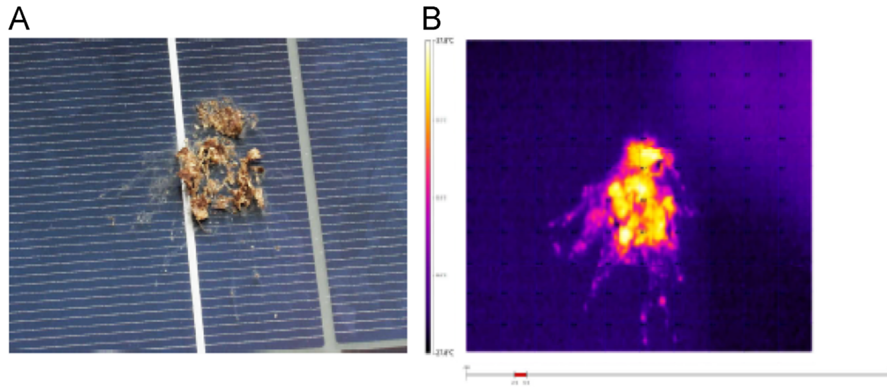

Fig. 9. The effect of bird dropping on the surface of PV panels [25]. (A) The real image of the deposition on the panel surface and (B) image of a deposition on the panel surface captured with the thermo-vision camera.

Table 1
Summary of the state of the art on dust effect on solar systems for the period of 1942 to the present [28].

Year	Reference	Location	Highlights
1942–1990	Hottel and Woertz [29], Dietz [4], Garg [30], Sayigh [5,6], Anagnostou and Forrestieri [31], Hoffman and Ross [32], Pettit et al. [33,34] and, Black and Curcija, Berg [35], Freez, Murphy and Forman [36], Nimmo and Saed [37], Hoffman and Maag [38], Roth and Pettit [39], Cuddihy [40], Pettit and Freese [34], Zakhidov and Ismanzhanov [41], Wakim [9], Bethea et al. [42], El-Shobokshy et al. [43], Berganov et al. [44], Bajpai and Gupta [45], Michalsky [46], Ryan et al. [47], Deffenbaugh et al. [48]	USA($\times$ 18), India, Saudi Arabia($\times$ 3), Kuwait ($\times$ 2), USSR($\times$ 2), Nigeria	• Most research focused on solar collector, mirror and glass • Mainly results from outdoor tests • Minimum and maximum period of study was from 6 days to 1 year, respectively. • Very little investigation was conducted on dust properties, dust accumulation characteristics and other environmental factors like wind, humidity, etc. • Contradiction between results gained from different experiments • Maximum degradation was 17% reported by Wakim in Kuwait after 6 days of experiment and minimum reduction reported by different references in the United State • Rarely experiment tested in different tilt angles except Dietz [3], Garg [30] and Sayigh et al. [5,6] • Most tests have been conducted in the United States and similar results reported
1990–2010	Said [49], Al-Alawy [50], Nahar and Gupta [51], Hassan and Sayigh [52], Pande [53], Goossens et al. [54,10], El-Shobokshy and Hussein [55,7], Alamoud [56], El-Nashar [57–59], Bowden et al. [60], Adanu [61], Kattakayam et al. [11], Becker et al. [62], Hammond et al. [63],Offer and Zangvil [64], Goossens and Van Kershaever [54,10], Biryukov [65,66], Mastecbayeva and Kumar [67], Asl-Soleimani et al. [68], Hegazy [69], Badran [70], Hassan et al. [71], Kobayashi et al. [72], Eliminar et al. [12], Kimber et al. [73], Al-Helal and Alhamdan, Clark et al.	Saudi Arabia($\times$ 5), Iraq, India($\times$ 4), Israel($\times$ 4), Kuwait, UAE($\times$ 3), Australia, Ghana, Germany, USA($\times$ 4), Iran, Egypt($\times$ 2), Japan	• Most focus has been on the performance of PV modules • In very small instances experiments have been done in different tilt angles • For characterisation of dust properties, most studies have been simulated under artificial dust • Few studies have investigated dust accumulation by considering other environmental factors • Particles and dust characteristics have not been investigated completely, particularly electrostatic characteristic of settling deposition • Investigation of the effect of dust settlement by considering concentration and spectral transmittance • Minimum and maximum period of study was from one week in Israel and 9 years in Iraq [49], respectively • Causing as much as 40% transmittance drop in distillate production, UAE [56]
2010 and Later	Vivar et al. [74], Yerli et al. [75], Mani and Philai [13], Miller and Kurtz [76], Ju and Fu [77], Ibrahim [78], Cabanillas and Munguia [79], Sulaiman et al. [14], Zorrila-Casanova et al. [80], Pravan et al., Jiang et al. [81], Kaldellis et al. [15,82,83], Qasem et al. [23,84], Al Busairi et al., Mekhilef et al. [85], Mohamad and Hasan [20], Sarver et al. [28], Ghazi et al. [27]	Australia, Turkey, India, China($\times$ 2), Kuwait ($\times$ 4), Mexico, Malaysia ($\times$ 2), Spain, Italy, Libya, UK	• Focus on PV module and glass surfaces • Minimum and maximum period of study was from 10 days in Kuwait [77] and one year in China and Spain [76,79], respectively • Very small instances of set up based on laboratory experiments and modelling • Few studies considered the effect of other environmental factors like water stain, shadow, bird dropping, etc. on the efficiency of PV • In a few cases, study has been done on the effect of dust on micro grid efficiency • Investigation on the effect of dust settlement considering concentration and spectral transmittance • A few studies focus on dust characteristics like shape, size, etc. • Some cases investigated the effect of dust on different types of PVs, Munguia [78], Qasem [22,83]

the thermo-vision camera, it can be clearly observed that the covered surface has the temperature increase up to 10 °C, namely from the normal temperature of the panel (27.8 °C) with no deposits, to the temperature of 37.5 °C, recorded on the dirty area (see Fig. 9).

Bird dropping makes hot spot as a part of solar module, which leads to local overheating. In this case, heat is produced instead of electrical power. It not only decreases the energy efficiency of solar modules but also reduces its life time significantly.

In 2013, Taouti et al. [26] indicated that the dust effect in Qatar is only about 10% after 100 days without cleaning. They studied both Amorphous Silicon (a-Si) and Crystalline Silicon (C-Si) PV panels and reported that the degradation due to dust effect was greater in the C-Si compared to that of a-Si. This is explained by the rise in temperature due to dust effect on the panels. However, this study presents a different effect of dust on a-Si and C-Si but it lacks an analysis of the type and quantity of dust in the region. Also it does not explain the effect of the tilt angles of the collectors. Their results have some differences with another study which shows that 100 days' accumulation of dust at Qatar at an optimum tilt of 17° North will result in at least 50% reduction in solar radiation. Ghazi et al. [27] conducted an experimental research on the effect of dust on glass transmittance under UK weather condition in six different title angles from 0° to 90° with horizontal during 3 months. The results showed merely 5–6% reduction of transmittance after one, two and three weeks of exposure due to the rainy weather condition.

Among reviews, Sarver et al. [28] carried out a comprehensive overview of deposition and dust settlement effect on the solar system in 2013. They also highlighted key studies, relationships, observations, and mitigation techniques, and evaluated and offered some other approaches for mitigation and future research. We conclude our findings by summarising the results of Travis et al.'s comprehensive study on dust effects on solar systems for the period of 1942 to the present (see Table 1).

3. Cleaning mechanisms

It is obvious from the above survey that cleaning mechanism is essential for the solar industry. Gaofa et al. [86] reviewed the various cleaning mechanisms for flat-plate PV systems. They also reported on dust accumulation in some regions of China where there are several large scale PV installations and reported more than 40% in panel efficiency reduction.

Cleaning normally is carried out by several methods depending on the region and the cost:

Method 1: Washing, using water jets which is expensive and labour intensive (Fig. 10A). For example in Saudi Arabia the cost of one litre of water is three times that of a litre of petrol, but this is not a problem in temperate zones.
Method 2: The use of air compressor, to blow away the dust, which results in a lot of dust suspended in the air, suitable only for small systems.
Method 3: A third method is to use a manual system whereby the panel is turned manually to a maximum tilt angle early in the morning or late in the evening to let the dust fall. Again this is energy and labour intensive and for a system with a constant tilt angle, it is not feasible.
Method 4: A fourth system is a mechanical system which employs brushes similar to wind screen wipers of motor cars to wipe the dust away. Bird droppings will not be cleaned using this system nor sticky dust which has cemented itself to the glass due to high humidity (Fig. 10B).
Method 5: One of the most effective methods is the use of a self-cleaning nano-film. This uses super-hydrophilicity material such as TiO_2 (Fig. 10C).
Method 6: The electrostatic dust removal prevention method was invented for the use on lunar applications. The method generates counter electric charge to balance the electrostatic charge available in the dust.

Overview of the global dust emission indicates that the main source regions are in arid areas such as the Middle East, and Central and South Asia (mostly topographically low) characterised by little rainfall (annual rainfall under 200–250 mm). Although the dust emission at the Southern Hemisphere is smaller, it is still important for countries in Southern America and North Africa [90]. These hot spots are associated with a high amount of suspended particles in the air which can be used as an indicator for the identification of accumulated dust on PV and consequently cleaning regime.

A recent extensive study carried out by the World Bank [91] outlines the particle matters smaller than 10 μm either suspended in the air or deposited on surfaces (PM10) in various countries around the world. From this study we have selected eleven countries to indicate the severity of dust accumulation. Fig. 11 shows the amount of dust existing in these countries.

Another important illustration is shown in Fig. 12 whereby the map of the world is shown with the dust intensity in different colours [92]. The darker colour indicates the higher level of dust.

These zones indicate a meaningful relationship with the world's different climate zones. For example, 4 different climate conditions such as dry, humid equator, humid temperature and

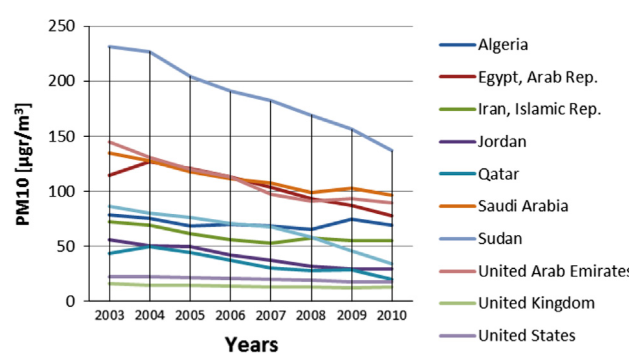

Fig. 11. PM10 for some countries in microgram/m^3, from 2003 to 2010 [91].

Fig. 10. Samples of PV cleaning mechanisms: (A) water spray cleaning mechanism [87], (B) self-cleaning robot [88] and (C) self-cleaning hydrophobic coatings (SCHN107™) layer, licensed by C-Voltaics [89].

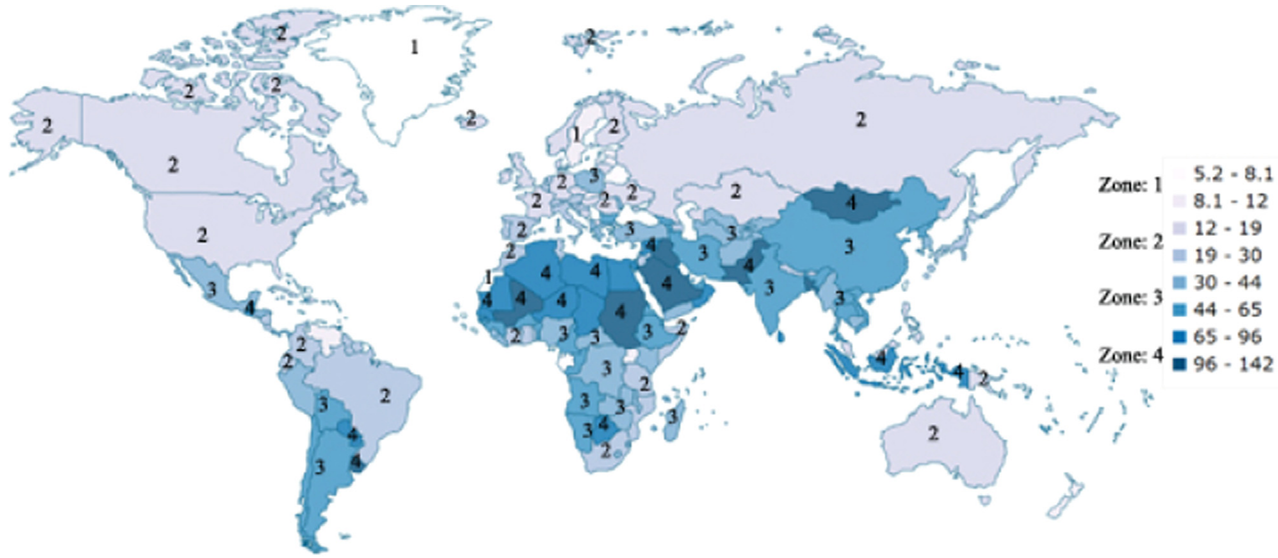

Fig. 12. PM10 world map [μg/m³], [92].

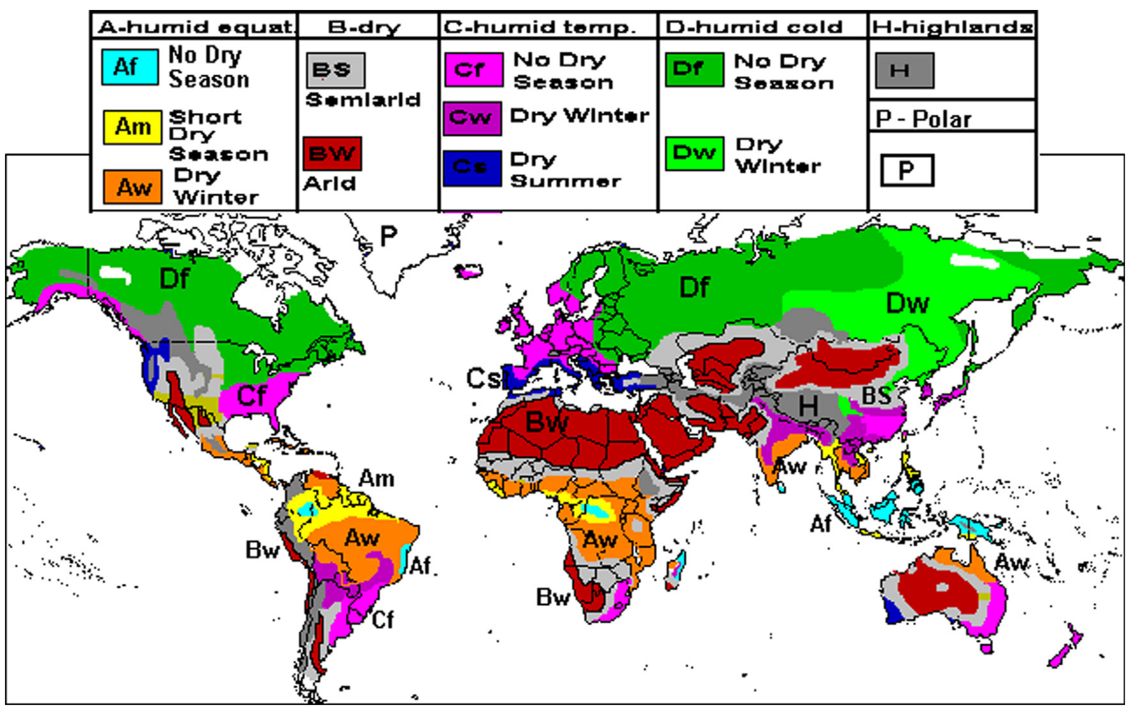

Fig. 13. World's different climate zones [90].

humid cold can be considered for zones 4, 3, 2 and 1, respectively. Fig. 13 shows the different climate zones in the world [90].

4. Final note

More than 500 articles have been published on this topic. They all emphasise the necessity of cleaning PV panels on a regular basis. It is important to make the surrounding area free of dust by planting short grass or concreting the zone.

5. Conclusions

Dust has widespread distribution in the world which settles on the surface of solar devices with very high potential and significantly reduces the system's efficiency. For example in one of the cleanest regions of the world, UK, it was discovered dust effect reduces the solar intensity by 5–6% if they were not cleaned after one month [27]. Sudan, for example, has worse dust accumulation 9 times that of UK fallen in one month without cleaning, [27]. "A dust layer of one-seventh of an ounce per square yard decreases solar power conversion by 40%," Mazumder explains [1]. "In Arizona, dust is deposited each month at about 4 times that amount. Deposition rates are even higher in the Middle East, Australia, and India [1]."

Deposited particles and dust effect on the surface of PV panels is a complex phenomenon varying by climate, environment and location. A surface in a dry desert-like location is subject to electrostatically attracted inorganic materials while a surface in a coastal area is subject to salts and rain driven dirt. Moreover,

Table 2
Cleaning cycle and mitigation method based on different climate conditions and characteristics.

Zone (based on PM10)	Climate condition	Cleaning cycle	Mitigation method
1	Humid cold	Every six months	• Wet type cleaning methods like: – Using a Solar Panel Cleaning Service – Solar panel cleaning by owner using soap and warm water
2	Humid temperature	Every three months	
3	Humid equator	Monthly	• Surface coating, particularly bi-functional coating or smart coating such as nano-surface coating for repelling rain and bird droppings and multifunctional coating including anti-reflective, self-cleaning and anti-fogging • Automatic cleaning systems for wiping snow and dust • Use a plastic mesh over PV panels to reduce the problem of bird droppings
4	Dry	Weekly	• Dry type cleaning methods like: – Rotary brush – Automated robotic device – Automated Self-Cleaning Technology like coating with hydrophobic, hydrophilic, anti-static, particularly nano-surface coating materials for large commercial or public utility sites, especially in remote and dry locations – Air hose/compressor

a surface in an industrial and cooler location is subject to organic windblown dirt, deposits from evaporated rain and atmospheric pollutants from fossil fuels. Generally, soiling of an exposed outdoor surface (such as a solar module) is a mix of organic and inorganic solids. Some of these solids are windborne whilst others are deposited from evaporated liquid (rain water, dew, fog). In very dry and desert like environment, most of the module soiling may be inorganic windborne solids (dust and dirt particles) that are electrostatically attracted to the solar module's glass surface as a result of dry winds. Additionally, some of this dust may consist of abrasive inorganic minerals (e.g. silica), which may scratch and damage the surface of the modules. In more cooler and wet environments, most of the module soiling may be organic deposits including windborne dirt, bird and other animal droppings, pollution (soot from burning coal or diesel), as well as decomposing organic plant matter from leaves, pollen, etc. When these materials become wet, they may be spread over the panel surface and further bond to it, causing potential corrosion and leaching of irons. In coastal areas, there may be salt deposits on the panel's surfaces resulting from water spray and rain driven dirt.

Many regions in the world have high solar intensity, but also have the largest dust quantity in the air. These areas are mostly North Africa and the Middle East. The dust phenomenon is clearly demonstrated in Figs. 11 and 12. Findings of this review along with the results obtained from other research around the world emphasise the prominence of cleaning the PV surfaces regularly. Hence, the authors recommend the following framework including cleaning cycle and mitigation methods in different climate conditions (Table 2).

It is clear that all cleaning mechanisms require expense and energy to operate. Therefore, one should choose the appropriate cleaning method suited for the specific location with minimum cost.

In addition, another recommendation is to place the solar devices at an angle to the horizontal no matter how small that angle is, in order to avoid maximum dust accumulation on their services. However a horizontal position must be avoided due to its maximum dust accumulation, as seen in Figs. 4 and 5.

If the solar device is placed in an area with high humidity or by the sea, this will result in a combination of the dust and the water to form a mixture which sticks to the surface of the device and is very difficult to remove it, see Fig. 8. Another important fact is that dust accumulation on the cover will lead to temperature increase which can be an additional problem in crystalline PV panels.

In the case of concentrating solar power devices (CSP) and in particular single dishes, the pitch angle should be set to zero early morning or late in the evening to drop slide off the dust, see Figs. 9 and 10.

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